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YSSP Report
Young Scientists Summer Program

Valorization of ecosystem services through location optimization of integrated value chains for biofuel and livestock production in Brazil

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Program: Biodiversity and Natural Resources (BNR)
30 September 2021

This research was funded by IIASA and its National Member Organizations in Africa, the Americas, Asia, and Europe.

ZVR 524808900

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Abstract

Future projections indicate an increase in food and energy demands, creating a pressure on land use, while there is an urgent global need for climate change mitigation. Bioenergy is foreseen as potential option to meet future energy demands and reduce greenhouse gas (GHG) emissions. However, the sustainability of biofuels depends on availability of biomass, logistics and impacts on ecosystems, that are strictly dependent on locations and regional characteristics. This study presents a bottom-up approach to assess spatially explicit sustainability of bioenergy-livestock integrated systems (BLIS) in Brazil, to understand their contribution to future energy demands and GHG mitigation targets, and their impacts on Ecosystem Services (bioenergy production, GHG mitigation, zero direct deforestation, reduction of food competition). The proposed integration considers livestock intensification and use of biofuels by-products as animal feed supplement, taking advantage of synergies between these two value chains. Three different technological options were considered, Tech1_Sugarcane considers an autonomous sugarcane plant producing ethanol, electricity, and animal feed; in Tech2_Corn, corn is processed during sugarcane offseason, producing ethanol, corn oil and animal feed (DGS); Tech3_Soybean considers a biodiesel plant integrated with sugarcane plant. Techno-economic and environmental implications of the three BLIS technological options were modelled using the Virtual Biorefinery, developed at LNBR/CNPEM. After exclusion of biodiversity hotspots, biomes and scattered feedstock production, 18 million hectares of pasture inside Sugarcane Agroecological Zoning could be available for BLIS expansion. Tech1_Sugarcane has the highest potential for bioenergy production (89 billion liters) and GHG mitigation (139 million tonnes of CO_2eq) among the technological options, and Tech3_Soybean presents the highest profits. Expansion of BLIS system in Brazil could contribute to meet future bioenergy demands and mitigation targets in the country while also alleviating pressure on land use for food and energy purposes, and without expanding on biodiversity hotspots and Pantanal and Amazon biomes. These results might help to support more assertive public policies regarding biofuel expansion in Brazil and contribute to achieve the ambitious targets assumed in the Paris Agreement.

Keywords: integrated value-chains, supply-chain assessment, spatial analysis, techno-economic analysis, life cycle assessment

Acknowledgments

I would like to thank my IIASA supervisors, Sylvain Leduc and Fulvio di Fulvio for having shared with me their vast knowledge and research experience in these YSSP months, and by their adaptability to make things work for this project even 10,000 km and 5 time-zones away. Also, I'd like to thank LNBR team for all the support to make this YSSP real for me. Special thanks to Thayse A. D. Hernandes not only for the support but also for all the shared knowledge and experience. Thank you Gabriel P. Petrielli and Daniele S. Henzler for all the inputs and positive energy. Thank you Otávio Cavalett and Tassia L. Junqueira, my PhD supervisors, that have been supporting and encouraging me all these years, helping me to grow professionally and personally. Final thanks to my fellow YSSPers for the shared talks and inspiration to make this YSSP remarkable even virtually.

About the author

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1. Introduction

Production systems to optimize land use and mitigate GHG emissions

Future projections indicate an increase in food and energy demands (Bauer et al., 2017; Popp et al., 2017; Riahi et al., 2017), creating a pressure on land use, while there is an urgent gloval need for climate change mitigation options (Roelfsema et al., 2020; van Soest et al., 2021). In this context, production systems that can optimize land-based outputs under climate change mitigation scenarios are key to meet future food and energy demands in sustainable way. Bioenergy is foreseen as potential option to meet future energy demands and reduce greenhouse gas (GHG) emissions (Daioglou et al., 2019; Frank et al., 2021; Jaiswal et al., 2017). However, the sustainability of bioenergy production depends on availability of biomass, logistics and impacts on the ecosystem, that are strictly dependent on location and regional characteristics (Hiloidhari et al., 2017; Humpenöder et al., 2018). Biomass productivity, previous land use, land conditions, soil and crop characteristics and climatic conditions demand site-specific assessment (Field et al., 2020; Granco et al., 2019; Zullo et al., 2018). There is a world trend to perform spatially explicit sustainability assessment and to regionalized life cycle impacts (Huijbregts et al., 2017; UNEP/SETAC, 2016; 2019). In an economic perspective, the biomass spatial distribution can generate high costs of recovery and transportation (Hiloidhari et al., 2017). Georeferenced sustainability impacts can be assessed integrating Life Cycle Assessment (LCA) with Geographic Information Systems (GIS) (Hiloidhari et al., 2017), and through spatially explicit optimalization of supply chains of bioenergy production, that can assess both economic and environmental impacts, such as costs and GHG emissions (Jong et al., 2017; Kim et al., 2018; Laasasehano et al., 2019).

Intensification of livestock production is one possible measure to release land for bioenergy production, without compromising meat production (Berndes et al., 2016; Cardoso et al., 2016; Santos et al., 2020). Besides, cattle intensification can minimize associated GHG emissions while also being cost-effective (Cardoso et al., 2016; Silva et al., 2017). Among production systems that can intensify land use in sustainable way while also mitigating GHG emissions, there is the bioenergy-livestock integration (Souza et al., 2021a). This system can happen by increasing cattle stocking rate or by finishing cattle in feedlots, this integration happens due to nutritional content as animal feed of bioenergy by-products (e.g., bagasse, yeast, distillers' grains, meal) (Souza et al., 2019; 2021a). Brazil has huge potential to achieve a broader implementation of bioenergy-livestock integrated systems (BLIS), due to its considerably high bioenergy and livestock production; for instance, the country produces around 30 billion liters of ethanol and 5 billion liters of biodiesel (CONAB, 2021b, ANP, 2021) and has about 214 million cattle heads (IBGE, 2021). Also, the country is committed to reduce GHG emissions by 2030 and increase the share of bioenergy in its energy matrix as on its Nationally Determined Contributions (NDCs) (MMA, 2015).

However, it is still unclear the potential contributions of these integrated systems to future energy demands and GHG mitigation targets in Brazil, and the impacts on ecosystems services associated with this expansion. In this context, the research questions addressed in this study include assess potential contributions of the integrated systems to future energy demands; assess the impacts of BLIS on the GHG mitigation targets in Brazil; and assess the impacts of BLIS expansion on ecosystems services. The main goal for this study was to identify best locations to expand BLIS while maximizing profits and minimizing GHG emissions and to assess the potential contribution of BLIS to future energy demands. For that, a spatially explicit sustainability assessment of BLIS expansion in Center-South region in Brazil was performed, considering land use restrictions (e.g., considering only pasture areas inside sugarcane agroecological zoning, no displacement of livestock). This assessment provided insights to identify optimal locations and optimal technological options of BLIS in Brazil, and considered the effects on zero direct deforestation, reduction of food competition and of possible biodiversity losses. The study was performed by integrating two models: Virtual Biorefinery (VB) developed by LNBR/CNPEM and BeWhere, developed by IIASA.

Optimization of bioenergy supply chain

Within the biofuels supply chain, five main stages are encompassed: biomass production, logistics, biofuel production, distribution, and use (Yue et al., 2014). Unlike fossil fuel supply chain, in bioenergy production, the feedstock (biomass) production stage is the most challenging (Yue et al., 2014). Although biomass production may be seasonal and has sparse spatial distribution, the supply and transportation to biofuel plants must be continuous and efficient (Garcia and You, 2015; Yue et al., 2014). Thus, the challenges lie in performing feedstock supply planning that is efficient in harvesting, pre-processing, storage, and transportation to the production stage (Garcia and You, 2015; Yue et al., 2014). Optimization models should combine detailed site-specific characteristics and impacts of biomass production, with variation in biomass productivity, different demands to be met, different carbon prices, among others. At first, supply chain optimization problems dealt only with achieving economic objectives, such as minimizing production costs or maximizing profits, for example. However, to analyze the sustainability of biofuels, it is necessary to meet environmental and social objectives as well, creating multi-objective optimization (Garcia and You, 2015).

BeWhere model was developed by IIASA and has been applied to solve the optimization of bioenergy production supply-chains from variable biomasses worldwide (Table 1). It uses mixed integer linear programming (MILP) to set optimal locations to implement plants based on biomass supply and demand points, and optimal technological options (Leduc, 2009; Wetterlund 2010), the model is written in the commercial software GAMS (Rosenthal, 2017) and uses a CPLEX solver. In BeWhere, the objective problem was solved by transforming environmental indicators into economic ones, as in the case of Harahap et al. (2019) and Mesfun et al. (2017), which transformed emissions into costs through carbon tax accounting, or through environmental constraints to be met, such as stipulated greenhouse gas emission reduction targets (Patrizio et al., 2018).

Table 1: Application of BeWhere to optimize bioenergy/biofuel supply-chain

Reference	Problem	Location
Harahap et al. (2019)	To find best palm oil biodiesel plant configurations and locations, maximizing supply chain profits.	Indonesia – Sumatra
Jong et al. (2017)	To find best locations, scale, technology, and configurations of forest biofuel plants, minimizing supply chain costs.	Sweden
Khatiwada et al. (2016)	To find best technology option for sugarcane bioenergy production, minimizing supply chain costs.	Brazil – São Paulo
Mandova et al. (2018)	To find best level of substitution of coal by biomass in steel mills, minimizing supply chain costs.	EU – 28
Mesfun et al. (2017)	To find best options to integration of renewable energy systems into energy supply, minimizing supply chain costs.	EU – Alpes region

Natarajan et al. (2014)	To find best location, scale and feedstock for biodiesel production, minimizing supply chain costs.	Finland
Patrizio et al. (2018)	To find best level of substitution of coal by biomass in steel mills, minimizing supply chain costs and meet targets of GHG mitigation	USA
Truong et al. (2019)	To find best potentials of co-firing biomass in coal plants, minimizing supply chain costs.	Vietnam
Wetterlund et al. (2012)	To find best location, size and configuration of biorefineries, minimizing supply chain costs.	Europe Union
Zetterholm et al. (2018)	To find best supply chain configuration of co-gasification biorefineries, minimizing supply chain costs.	Sweden

2. Methods

This study was performed as a bottom-up approach to assess the potential contribution of BLIS to future energy demands derived from the narratives of Shared Socioeconomic Pathways (SSPs) in Brazil (Andrade Jr. et al., 2019). By identifying potential locations to implement BLIS in Brazil, this study assessed the impacts of BLIS expansion on ecosystem services such as bioenergy production, GHG mitigation, zero direct deforestation, and reduction of food.

The integration considered livestock intensification and use of biofuels by-products as animal feed supplement, taking advantage of synergies between these two value chains, and it was built upon positive experiences from pioneer projects in Brazil and in other countries (e.g., USA). As definition, all crops for cattle feed and for bioenergy production must be produced inside the integration boundaries to avoid land use change and/or displacement of livestock production. Data for the BLIS modelling, and environmental and economic parameters were collected from literature, and meetings with experts. Figure 1 represents the schematic diagram of the tools, methods and models applied in this study and the outputs from each one of them. The spatial assessment was performed using ArcGIS software to derive potential available area to expand BLIS in Brazil. Then, spatially explicit assessment of BLIS production, GHG emissions and profits were modeled in VB for all the available area. The preparation of the integration between the VB model and the BeWhere model was carried out. The optimization run on BeWhere will deliver the best technological options and locations to implement new BLIS plants in Brazil.

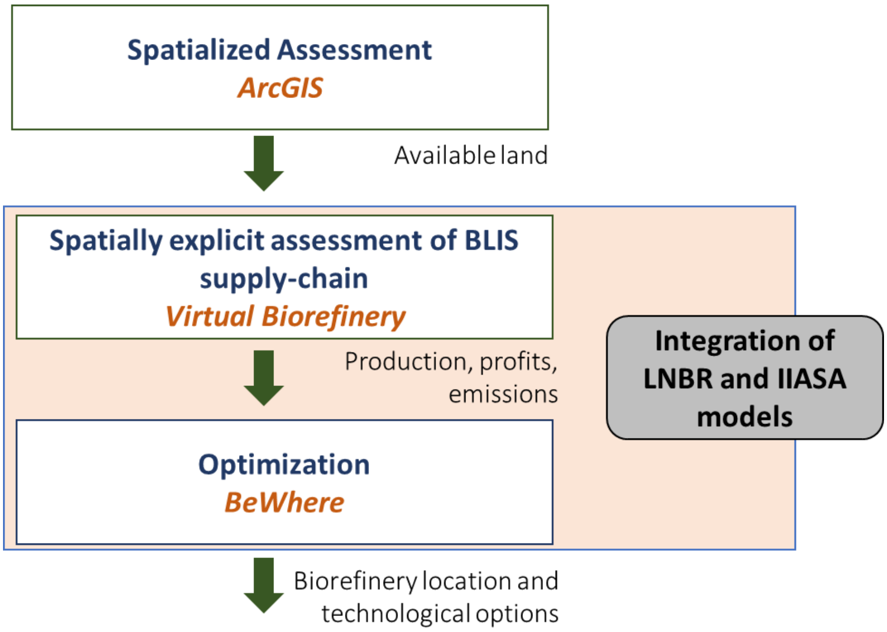

Figure 1: Schematic diagram of the methodology proposed in this study

Spatialized Assessment

Available area for BLIS expansion

This study considered six Brazilian states, highlighted in blue in Figure 2: São Paulo, Mato Grosso, Mato Grosso do Sul, Paraná, Minas Gerais and Goiás. These states are responsible for 94% of corn produced in rotation with soybean (named second season corn), 90% of sugarcane production, 67% of soybean production, and 54% of beef cattle production (IBGE, 2021a; 2021b; 2021c).

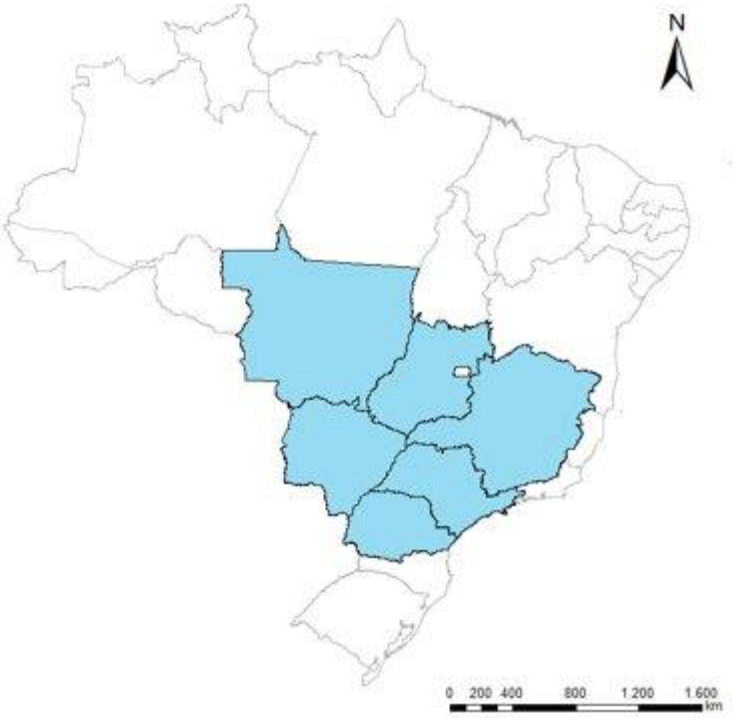

Figure 2: Study area in Brazil – six states from Center-South region

Within these six states, we (a) excluded biodiversity hotspots, (b) excluded Amazon and Cerrado biomes, (c) considered only pasture areas inside Sugarcane Agroecological Zoning (SAEZ) as potential for expansion, (d) excluded polygons with area smaller than 40 hectares. Biodiversity hotspots are based on MMA (2007; 2017) classification of areas with considerably importance for nature and biodiversity conservation. An update of Hernandes et al. (2021) study was performed, considering the most recent land use in Brazil, to account for what is still pasture inside SAEZ. The current use and occupation of the remaining areas of the SAEZ were classified according to the maps provided by the MapBiomas network (MapBiomas, 2020). The SAEZ was developed in 2009 taking into consideration climate, hydrological and soil aspects (Manzatto et al., 2009), it excludes land with a slope greater than 12%; areas with native vegetation cover; the Amazon and Pantanal biomes; areas of environmental protection; indigenous lands; forest remnants, dunes, mangroves, escarpments and outcrops of rock, reforestation, urban and mining areas; and areas with sugarcane production in the year it was developed.

Modelling and simulation of BLIS supply-chain

The Virtual Biorefinery

The complete assessment of the supply-chain of BLIS was performed on the VB (Bonomi et al., 2016), developed by the Brazilian Biorenewables National Laboratory (LNBR/CNPEM). This platform simulates techno-economic and environmental impacts of production chains of biorenewables, combining georeferenced data from the spatialized assessment, mathematical models and simulation tools of the entire production chain (i.e., agricultural, industrial, logistics, and product use phases). In this study, inventories of GHG emissions and profits of the BLIS supply-chain were created using VB, considering agriculture production (e.g., sugarcane, corn, soybean and cattle), logistics from agricultural to industrial plants (e.g., transportation of inputs, feedstocks and residues), and industrial conversion (e.g., ethanol, electricity, biodiesel).

Sugarcane yield was modelled in the Crop Assessment Tool (Souza et al., 2021b) that implements the Agroecological Zone methodology (AZM) developed by the Food and Agricultural Organization (FAO) (Allen et al., 1998), considering climatic data from 35 years (1980-2015) in a spatial resolution of 27 km x 27 km (Xavier et al., 2015). Availability of sugarcane straw to be recovered to generate electricity was based on the suitability map developed in Souza et al. (2021c) study, considering 120 kg of straw (dry basis) per tonne of sugarcane produced (wet basis) (Menandro et al., 2017). The agriculture stage of production and transportation of main products, residues and inputs were simulated in CanaSoft ® (Cavalett et al., 2012) for sugarcane, for second season corn produced in rotation with soybean, and for beef cattle production. Data for production of corn and soybean in rotation was based on Matsuura and Picoli (2018), livestock modeling was based on Souza et al. (2019), Matsuura and Picoli (2018) and Picoli (2017). Modeling of industrial stage was performed in simplified models based on simulations from VB (Souza et al., 2019; Bonomi et al., 2019; Milanez et al., 2014; Moraes et al., 2014; Junqueira et al., 2016; Dias et al., 2016).

Technological options of BLIS

Three different technological options were considered in this study: Tech1_Sugarcane; Tech2_Corn and Tech3_Soybean. Tech1_Sugarcane considers an autonomous sugarcane plant producing ethanol, electricity and animal feed; sugarcane cannot be storage and operates only during part of the year; thus, in Tech2_Corn, corn is processed during sugarcane offseason, producing ethanol, corn oil and animal feed (DGS); finally, Tech3_Soybean considers a biodiesel plant integrated with sugarcane plant. Detailed description of these three technological options in presented in Table 2 and in Figure 3.

In Tech1_Sugarcane, corn and soybean production is only to meet the necessary corn and soybean meal requirements of cattle feed. When there is ethanol from corn, there is an iterative calculation to share the available area for corn/soybean and sugarcane, since the sugarcane plant size defines the corn processing, and the corn processing defines the necessary area to produce corn, that defines available area for sugarcane production. Corn processing capacity is restricted to available LCM material to operate CHP during offseason and by daily volume of sugarcane ethanol production, since the same equipment is used, also, the corn plant cannot operate more than 130 days per year. The process considers dry grind pathway, with ethanol, distillers' grains with solubles (DGS) (i.e., animal feed) and corn oil production. The plant operates during the sugarcane offseason supplied by sugarcane CHP extended operation. Soybean oil extraction and transesterification plants operate integrated with the sugarcane plant 200 days per year, using ethanol in the process (Olivério et al., 2014). In Tech2_Corn and Tech3_Soybean, necessary corn in cattle feed is replaced by DGS a proportion of 1:1 (Hoffman and Baker 2011). In the agricultural phase, manure from cattle on feedlots is applied on sugarcane field to replace part of N fertilizer (Matsuura and Picoli, 2018).

In all technological options, the total available area is shared among production of sugarcane, corn, and soybean. Main industrial parameters for BLIS are presented in Table 3. Sugarcane plants are autonomous and operate 200 days per year. The processing capacity depends on available area and sugarcane modelled yield. The main product is anhydrous ethanol and electricity is produced using biomethane from vinasse anaerobic digestion (Moraes et al., 2014; Junqueira et al., 2016) and lignocellulosic material (i.e., sugarcane bagasse and straw) burnt in boiler for combined heat and power generation (CHP). After the sugarcane milling, part of bagasse is diverted to feed production and the remaining is sent to the CHP with straw. Electricity generation vary depending on the site-specific recovery rate. The plant produces feed only if there is enough lignocellulosic material (LCM) material to meet the main plant energetic demands. Second season corn is always produced in rotation with soybean. Feed production and composition is based on Souza et al. (2019). Considered corn and soybean yields are presented in Table 4. Cattle stocking rate before integration was assumed to be 1 head per hectare for all the study area and each hectare of expanded crop must meet the nutritional requirements of one cattle head. The feedlots parameters are based on Souza et al. (2019).

Table 2: Definition of the three assessed scenarios

	Tech1_Sugarcane	**Tech2_Corn**	**Tech3_Soybean**
Description	Sugarcane plant production cattle feed. Cattle finished in feedlots.	Sugarcane ethanol plant, with corn processing during sugarcane offseason. Cattle finished in feedlots.	Sugarcane ethanol plant, with corn processing during sugarcane offseason. Soybean biodiesel production integrated with sugarcane plant.
Main product	Sugarcane ethanol	Sugarcane and corn ethanol	Sugarcane and corn ethanol
Co-products	Surplus animal feed (soybean meal), soybean oil, electricity, red meat	Surplus animal feed (soybean meal and DGS), soybean oil, corn oil, electricity, red meat	Surplus animal feed (soybean meal and DGS), soybean biodiesel, corn oil, electricity, red meat

Table 3: Main parameters of BLIS

Parameters	Value	Unit
Sugarcane plant		
Electricity from biomethane	3	kWh/t sugarcane
Steam yield	2	kg steam/kg LCM, 50% moisture
Steam consumption	350	kg/t sugarcane
Energy consumption	30	kWh/t sugarcane
Energy consumption (straw)	25	kWh/t straw
Ethanol yield	85	l/t sugarcane
Soybean oil extraction		
Soybean oil yield	190	kg/t soybean
Soybean meal yield	800	kg/t soybean
Steam consumption	271	kg/t soybean
Energy consumption	35	kWh/t soybean
Soybean biodiesel plant		
Biodiesel yield	956	kg/t soybean oil
Glycerin yield	117	kg/t soybean oil
Steam consumption	300	kg/t soybean oil
Energy consumption	15	kWh/t soybean oil
Corn ethanol plant		
Ethanol yield	403	l/t corn
DDGs yield	171	kg/t corn
Steam consumption	345	kg steam/t corn
Energy consumption	106	kWh/t corn
Cattle on feedlot		

Duration	120	Days
Feed	22	kg/head.day
Meat yield	55	%, mass basis
Slaughter weight	480	Kg

Table 4: Corn and soybean yields on the study area

Yield	Soybean (t/ha)	Corn (t/ha)
Paraná	3.3	5.4
Mato Grosso do Sul	3.2	4.8
Mato Grosso	3.2	5.7
São Paulo	3.2	4.8
Minas Gerais	3.1	5.1
Goiás	3.1	5.9

Source: IBGE (2021a; 2021b; 2021c)

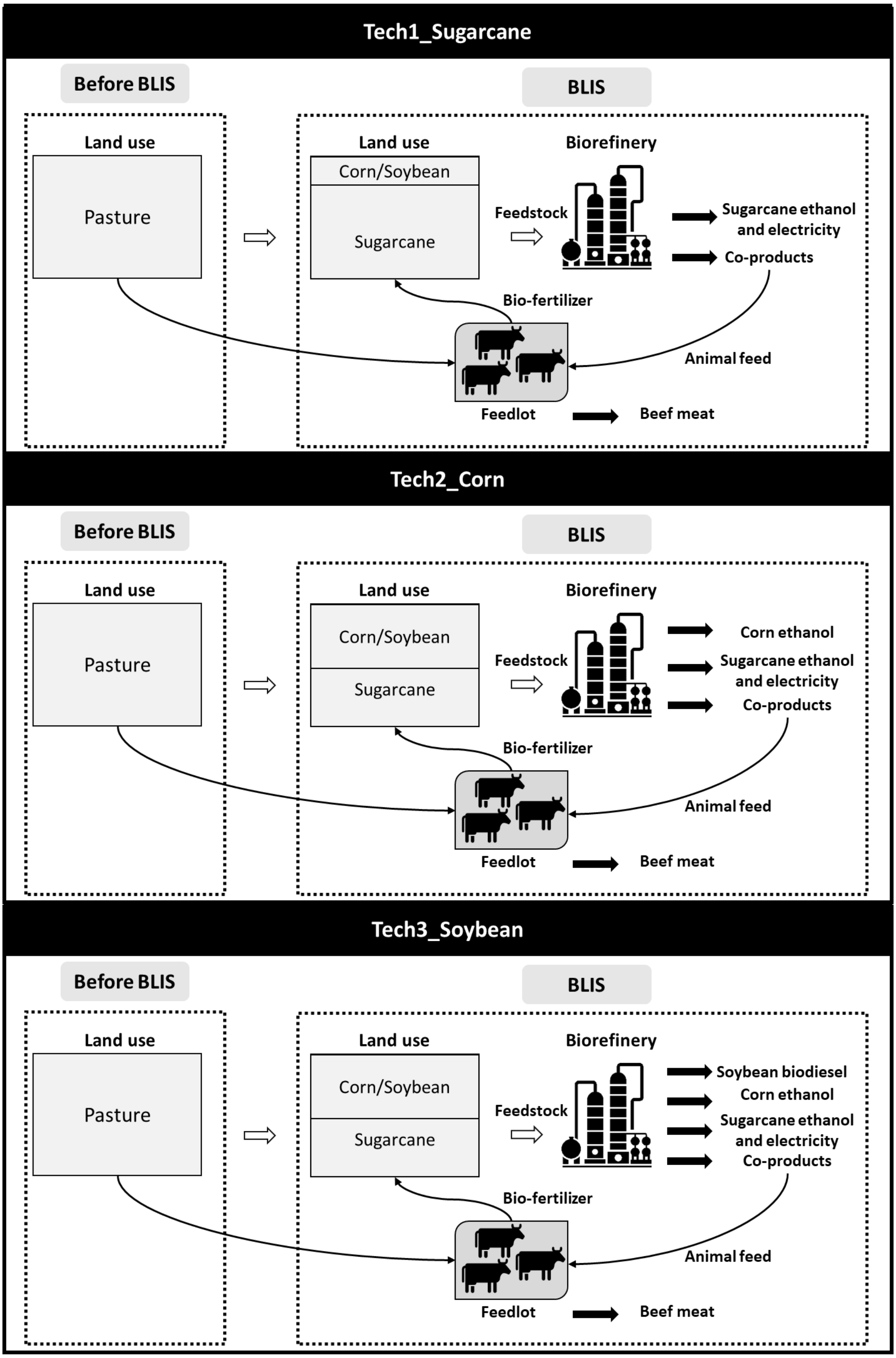

Figure 3: Overview of three technological options of BLIS

Supply-chain GHG emissions and profits

The GHG emissions for the integrated systems are calculated using a Life Cycle Assessment (LCA) methodology, using inventories generated by VB model. The focus of this study was on the GHG emissions of BLIS technological options. The functional unit is 1 MJ of ethanol in a cradle-to-gate approach, using energetic allocation among products. Recipe Midpoint 2016 (Huijbregts et al., 2017), method was applied using Global Warming category that measures GHG emissions in CO_2eq. Avoided emissions are the difference among carbon intensities of ethanol and gasoline carbon intensity (i.e., 87.4 gCO_2eq/MJ), and of biodiesel and diesel (i.e., 86.5 gCO_2eq/MJ) (Matsuura et al., 2018).

CanaSoft® generates an environmental inventory that includes emissions to air, soil, and water from the production and application of NPK fertilizers (nitrogen, phosphate, and potassium), soil correctives, and agrochemicals; fuel production and burnt on agricultural operations; machinery production and use; and application of agro-industrial residues on the field (e.g., sugarcane vinasse, filter cake, ashes). Industrial inventory considers the effects of chemicals, biomass (such as sugarcane bagasse and straw) burned in boilers and building materials.

The costs of the supply chains are calculated using the inventories derived from the VB. The supply-chain profits are the difference from revenues and costs, that rely on cash flow analysis. The cash flow analysis depends on capital expenditures (CAPEX): investment in buildings, equipment, herd, working capital, etc; on revenues: based on market prices of main outputs such as ethanol, sugar, electricity, beef cattle, and others (Table 5); and on operating costs (OPEX): costs associated with feedstock, labor, maintenance, inputs, utilities, feed, etc. The annualization of CAPEX was performed considering 25 years of expected plant lifetime and a discount rate of 12% per year. Economic values consider December 2019 as reference, when 1.0 US$ equaled 4.0 R$. The feedstock and transportation costs vary depending on the site location. Sugarcane plant investments are calculated on VB and were adjusted to varying processing capacities of feedstock.

Table 5: Considered market prices for products and co-products of BLIS

Products	**Price**
Ethanol (R$/l)	1.94
Electricity (R$/MWh)	211.1
Soybean meal (R$/kg)	1.7
Soybean oil (R$/kg)	2.7
Biodiesel (R$/kg)	3.5
Glycerin (R$/kg)	2.2
DGS (R$/kg)	0.7
Corn oil (R$/kg)	2.8
Cattle, in live weight (R$/kg)	9.9

Integration of Virtual Biorefinery and BeWhere

Spatially explicit assessment of GHG emissions and profits of BLIS

The main task of this work was to integrate the VB and BeWhere models. The approach to integrate these two models is presented in Figure 4. The VB was adapted to the georeferenced assessment, considering each grid cell as a production site, and generated the necessary economic and environmental inventories to perform the spatially explicit sustainability assessment, considering the regional characteristics to produce biofuels.

In several regions of the study area, biomass production is relatively low and scattered, so that it would be necessary to source biomass from long distances to achieve the minimum viable processing of a sugarcane mill, which could be economically unviable. For this, we performed a preliminary assessment carrying out agglomeration of grid cells to determine potential sites for implementation of new biorefineries, respecting some restrictions. It was considered a maximum average radius allowed for the plant (approximately 40 km), minimum and maximum processing sizes (2 to 8 million tonnes processed annually, considering only sugarcane production), and restriction of the maximum number of grid cells to be clustered (up to 5), so as not to exceed the maximum radius allowed. The agglomeration was carried out using ArcGIS and python programming.

The cradle-to-gate costs, revenues and GHG emissions were calculated per candidate site to map potential ethanol production, potential avoided GHG emissions and potential profits. At the same time, VB inventories were adjusted and converted to be read by BeWhere model, this stage of the framework was performed using python programming. Finally, some BeWhere optimizations were carried out on GAMS, inserting the VB data and also writing the codes for future optimization, better described on the next section.

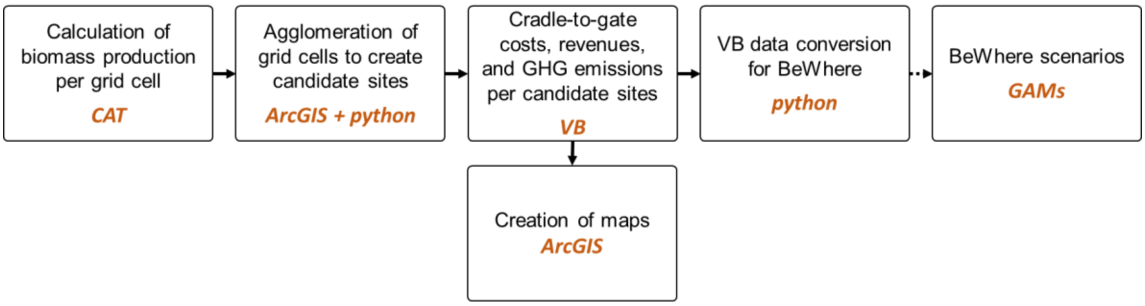

Figure 4: Diagram of VB and BeWhere integration approach

Optimization

Optimal locations to implemented BLIS in Brazil will be defined using BeWhere with data generated on VB model. The optimization will be a snapshot for the years 2020, 2030, 2040 and 2050, with the objective of maximizing total profit. Total profit will be calculated as the difference in revenues and costs per candidate site, considering the cradle-to-gate costs (i.e., CAPEX and OPEX) and revenues, distribution costs from candidate site to demand point, revenues with carbon credits (i.e., avoided GHG emissions), and distribution GHG emissions from candidate site to demand point. The maximization of profit will be restricted to available feedstock supply and cattle feed requirements. The costs and emissions associated with fuel distribution will be calculated considering the distance between each one of the candidate sites to each one of the demand points, calculated on ArcGIS with the available network infrastructure of roads in the study area. The distribution will be simplified, considering only the routes from network infrastructure to the demand points, using freight costs from the National Land Transport Agency (ANTT) (Brazil, 2020) and GHG emissions inventories from Ecoinvent 3.5 (Ecoinvent, 2018).

The future ethanol demands are those from Andrade Jr. (2019) study that interpret them for SSP1, SSP2 and SSP3 narratives (Table 6). The SSPs provide a better understanding of future global demands of economic sectors taking into consideration narrative storylines of challenges to adaptation and mitigation of climate change that combines social, economic and environmental trends (e.g., future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources) (O'Neil et al., 2017, 2014; Riahi et al., 2017).

SSP 1: Sustainability—Taking the green road considers low challenges to adaptation and mitigation due, mostly, to high levels of education, income growth, low population, reduction in inequality, strong institutions prioritizing sustainable development and a society aware of social, cultural, and economic costs of environmental degradation. The scenario presents modern energy, technological development, low patterns of energy consumption and social acceptability for renewable energy and bioenergy, which leads to a reduction in fossil fuel consumption (Bauer et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017; van Vuuren et al., 2017).

SSP 2: Middle of the road is not only an extrapolation of current trends but includes historical patterns such as emerging economies growing quickly and then slowing down after reaching higher levels of income, and also uneven growth patterns among countries. Overall, this uneven development reflects is an intermediate scenario compared to SSP1 (low challenges to mitigation and adaptation) and SSP 3 (high challenges for both mitigation and adaptation). There is a medium population growth, medium energy intensity, a gradual reduction of fossil fuel consumption and energy use, and a moderate modernization of final energy mix (Bauer et al., 2017; Fricko et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017).

In ***SSP 3: Regional rivalry—A rocky road***, the countries are concerned with local development, which negatively affects the global development and generates inequality. The slow growth in income and technological improvements, together with ineffective institutions (i.e., environmental concern) and low investments in education leads to high population growth (mostly in developing countries) and high challenges to both mitigation and adaptation. It presents high resource intensity and fossil fuel dependence and environmental degradation, due to low priority for environmental concerns. In the energy sector, the traditional bioenergy remains important; there is low technological development and high fossil fuel dependence (Bauer et al., 2017; Fujimori et al., 2017; O'Neil et al., 2017, 2014; Popp et al., 2017; Riahi et al., 2017).

Table 6: Future ethanol demands per SSP per decade for Brazil

Products	**2020**	**2030**	**2040**	**2050**
SSP1 (EJ)	0.9	1.4	1.6	1.5
SSP2 (EJ)	0.7	1.0	1.1	0.8
SSP3 (EJ)	0.6	0.7	0.8	0.5

To define the ethanol distribution points, we considered that the current demand share per municipality in Brazil will remain in the future. We normalized the total demand for the ten largest cities in terms of ethanol demand in Brazil (Table 7).

Table 7: Distribution points for ethanol demand in Brazil.

State	City	Demand share (%)	Normalized Demand share (%)
São Paulo	São Paulo	11.9%	45.2%
Goiás	Goiânia	2.2%	8.5%
Minas Gerais	Belo Horizonte	2.2%	8.4%
São Paulo	Campinas	1.7%	6.5%
Paraná	Curitiba	1.6%	6.0%
Rio de Janeiro	Rio de Janeiro	1.5%	5.8%
São Paulo	Ribeirão Preto	1.4%	5.3%
Mato Grosso	Cuiabá	1.4%	5.1%
São Paulo	Guarulhos	1.2%	4.6%
São Paulo	Sorocaba	1.2%	4.5%

The optimization will consider a variable carbon price per carbon credit generated (i.e., tonne of avoided CO_2eq emission). The prices derive from SSPs narratives per decade for Latin America (Riahi et al., 2017), presented in Table 8.

Table 8: Carbon prices considered for Brazil (R$/tonne of avoided CO_2eq emission)

Scenario	2020	2030	2040	2050
SSP1	24.2	90.0	197.3	274.9
SSP2	45.9	94.4	143.0	233.0
SSP3	-	-	305.4	506.7

3. Results and discussion

Available area for BLIS expansion

After excluding biodiversity hotpots, Amazon and Cerrado biomes and considering current pasture areas inside SAEZ, this study estimates Brazil has about 18 million hectares suitable to expand BLIS systems, divided in 1696 grid cells, represented in Figure 5, with the location of the ten demand points. Each grid cell has a specific available area for expansion, sugarcane, corn and soybean yield, and straw recovery rate.

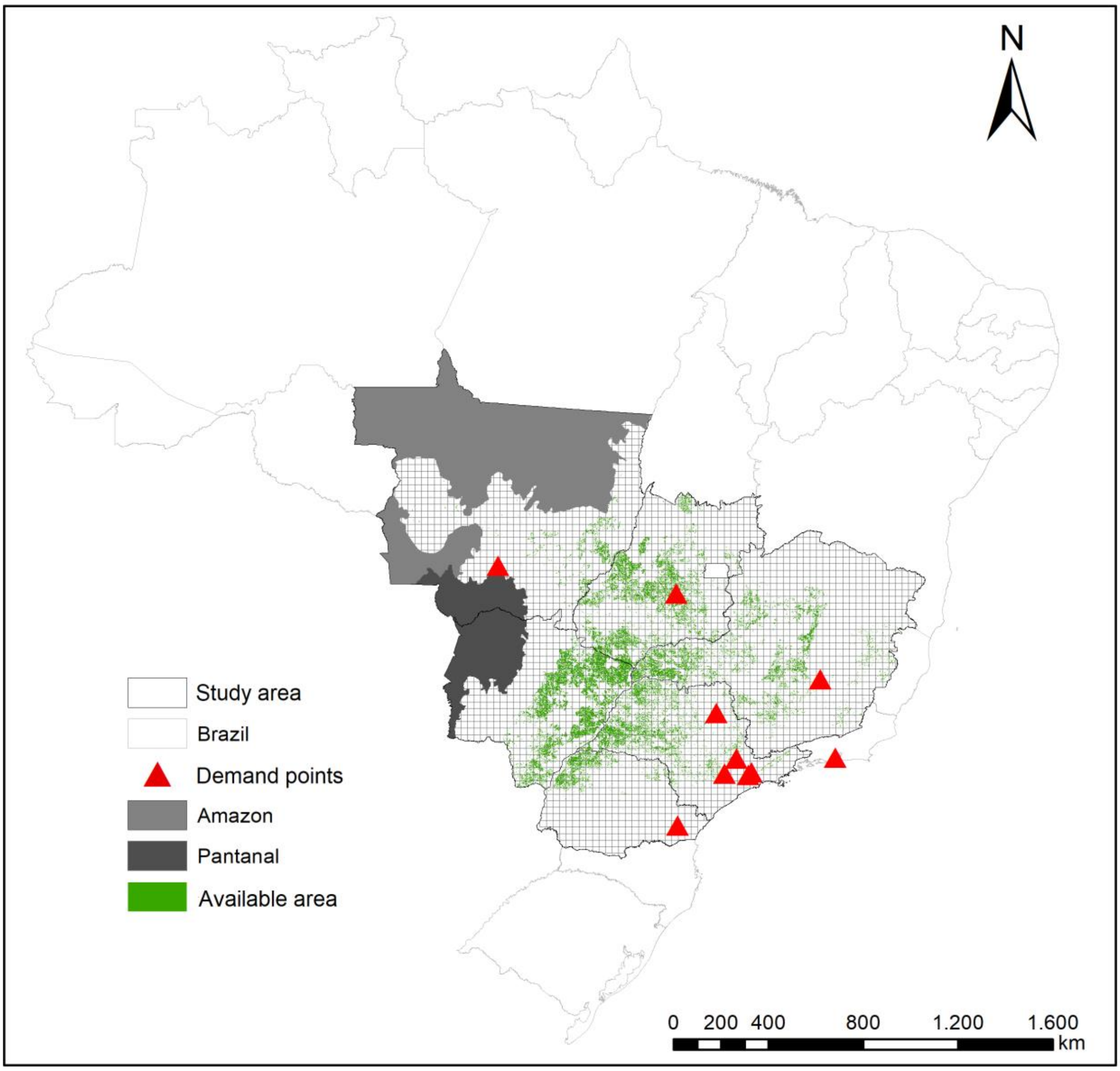

Figure 5: Available area for BLIS expansion and considered ethanol demand points in Brazil

Spatially explicit assessment of BLIS supply-chain

Considering sugarcane plant as the principal conversion system that supports the corn and soybean plants, we started our assessment calculating how much sugarcane could be produced per grid cell. The result is presented in Figure 6, only 14% of total grid cells could produce more than 2 million tonnes of sugarcane per year, our cut off value for minimum production. Most of grid cells could produce less than 1 million tonne per year, which means biomass supply is too spread.

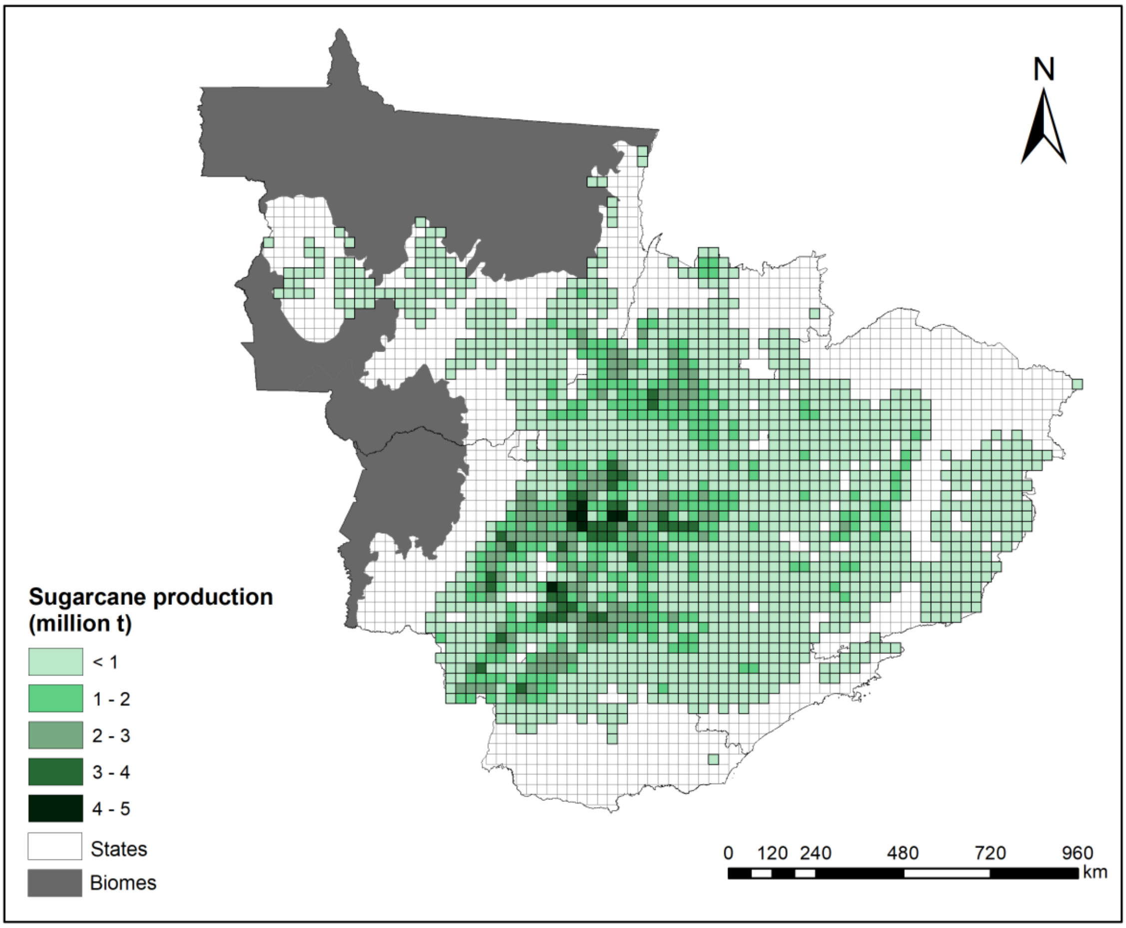

Figure 6: Spatially explicit sugarcane production in total available area for expansion

We performed the agglomeration of grid cells in candidate sites to run VB for the technological options. From the total 18 million hectares, after agglomeration, 2 million hectares were excluded, and they represent grid cells that were too isolated (mostly in Mato Grosso state) and couldn't meet the maximum radius restriction. In Figure 7 and 8 there is the visual representation of the spatially explicit sugarcane production in technological options 1, 2 and 3, respectively in the total 316 candidate sites. In the case of BLIS, not only sugarcane is produced in the available area, but all feedstocks for cattle feed also need to be produced within the available area, as definition to avoid displacement of land, in the case if Tech1_Sugarcane, only a small portion of the area is used for corn production in rotation with soybean, and most of candidate sites produce around 3 to 5 million tonnes of sugarcane per year. However, for Tech2_Corn and Tech3_Soybean, more land is used to produce corn and soybean and less sugarcane is produced, as illustrated in Figures 8 and 9. Sugarcane production is up to 2 million tonnes per year in most of candidate sites, which means that in order to have higher sugarcane processing capacities, closer to the Brazilian reality of around 4 million tonnes per year, more grid cells should be agglomerated for Tech2_Corn and Tech3_Soybean, however, to a better comparison, we kept the same amount of candidate sites and available area per site for all technological options.

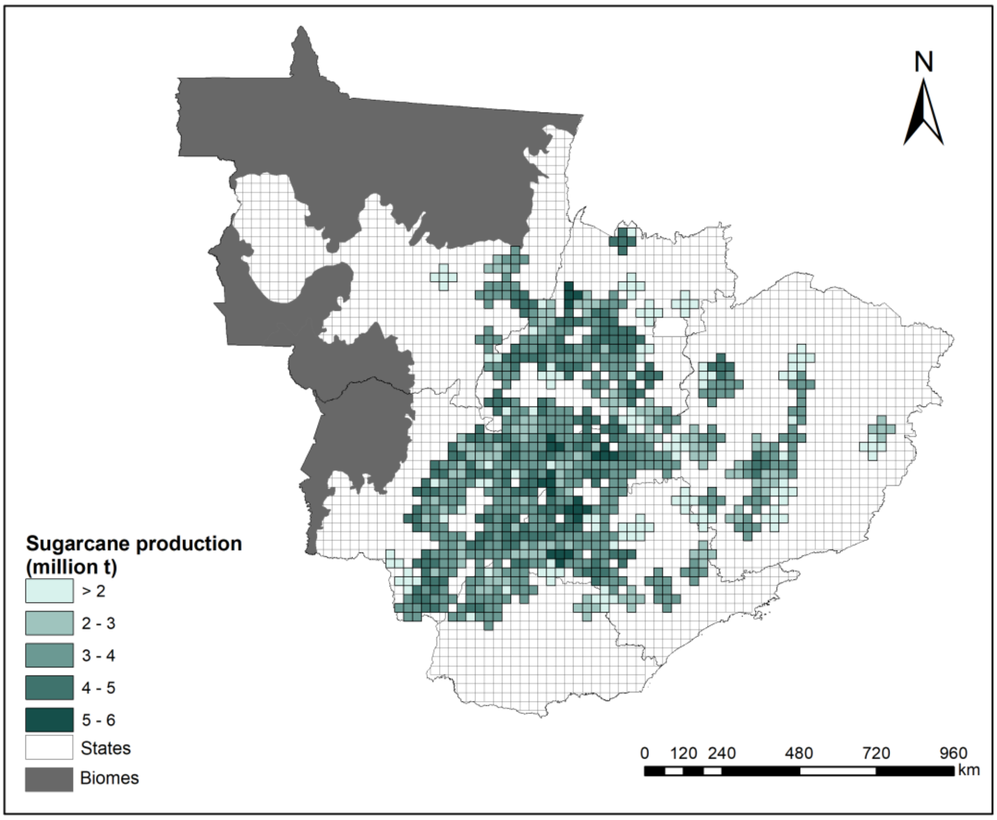

Figure 7: Spatially explicit sugarcane production in Tech1_Sugarcane after agglomeration

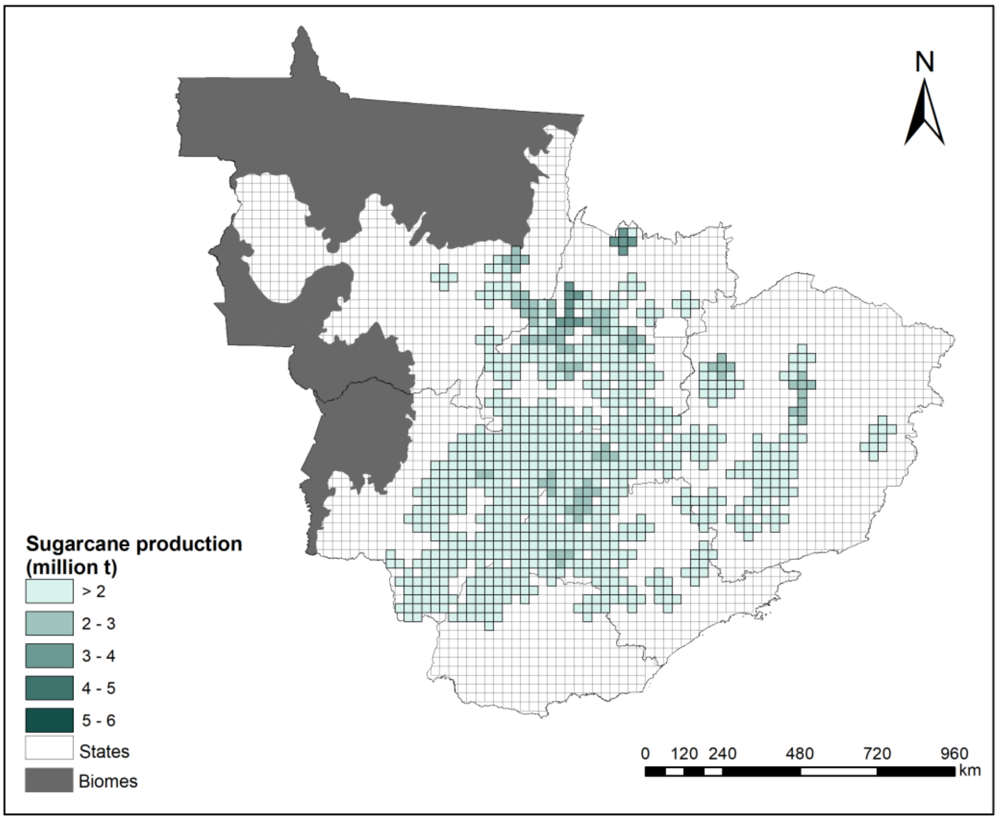

Figure 8: Spatially explicit sugarcane production in Tech2_Corn and Tech3_Soybean after agglomeration

Although Tech2_Corn has corn ethanol to complement sugarcane ethanol production, when comparing corn and sugarcane ethanol in the same area, less corn ethanol is produced due to considerably lower agricultural yields (Figures 9 and 10). Corn average agricultural yield (5 t/ha) is too small compared to sugarcane yield (75 t/ha). In Tech1_Sugarcane, a large amount of candidate sites produces more than 350 million liters of ethanol per year, while in Tech2_Corn and Tech3_Soybean, this number is less than 250 million liters of total ethanol. When comparing Tech2_Corn and Tech3_Soybean (Figures 10 and 11), a relatively small amount of ethanol is used to produce biodiesel, so less ethanol is available in this last option, but this difference is considerably small to be visualized in the maps.

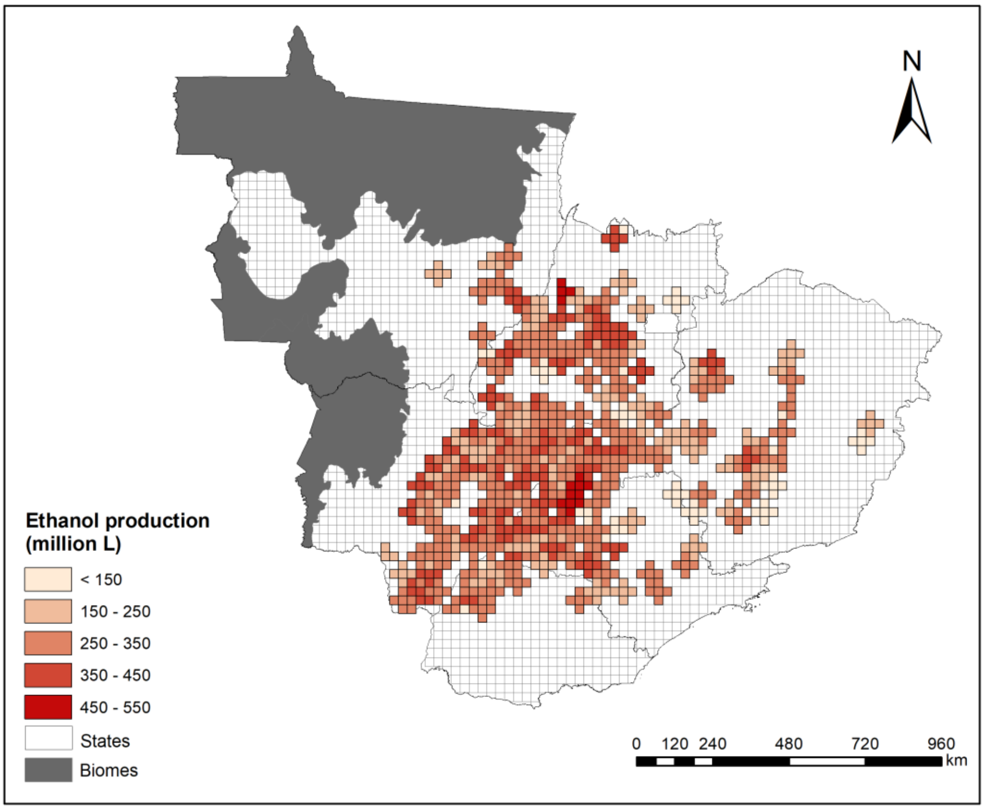

Figure 9: Spatially explicit potential ethanol production in Tech1_Sugarcane

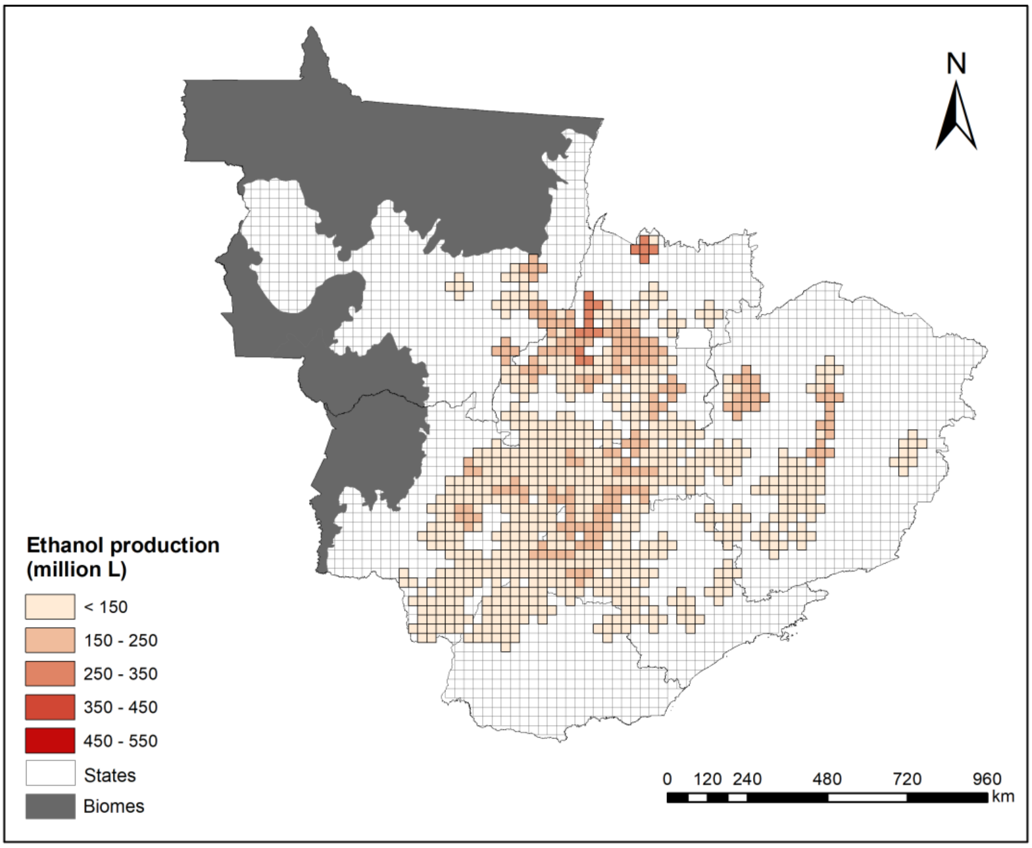

Figure 10: Spatially explicit potential ethanol production in Tech2_Corn

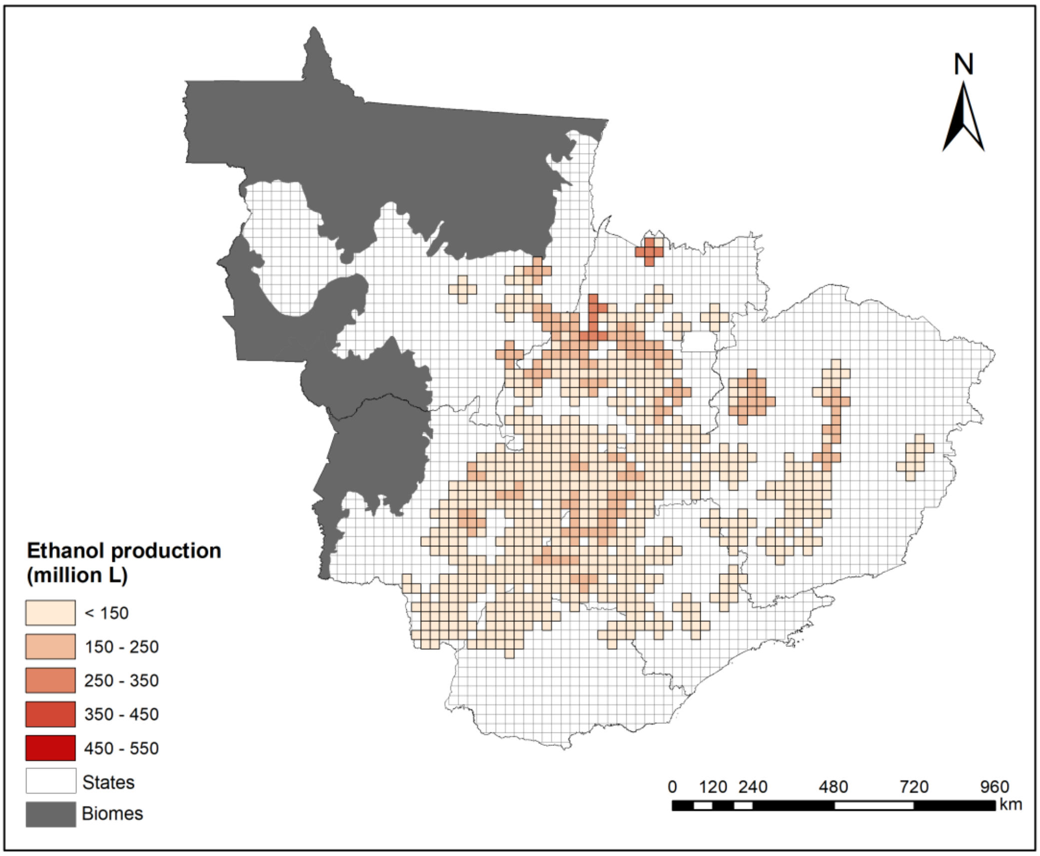

Figure 11: Spatially explicit potential ethanol production in Tech3_Soybean

When considering potentials of avoided GHG emissions, Tech1_Sugarcane has the highest potentials (Figure 12), of around 0.4 to 0.8 million tonnes of avoided CO_2eq per candidate site. Again, since considerably less ethanol is produced in Tech2_Corn, this technological option presented lower potential (Figure 13), with average avoided emissions of around 0.3 million tCO_2eq per candidate site. However, when comparing Tech2_Corn and Tech3_Soybean, the latter presents higher potential since biodiesel is also produced (Figure 14). Ethanol carbon intensity ranged from around 12 to 23 gCO_2eq/MJ in the three technological options. Brazilian average carbon intensity of 1G sugarcane ethanol is around 21 gCO_2eq/MJ (Matsuura et al., 2018). The lowest values could be found in candidate sites with high sugarcane yield and high straw recovery rates.

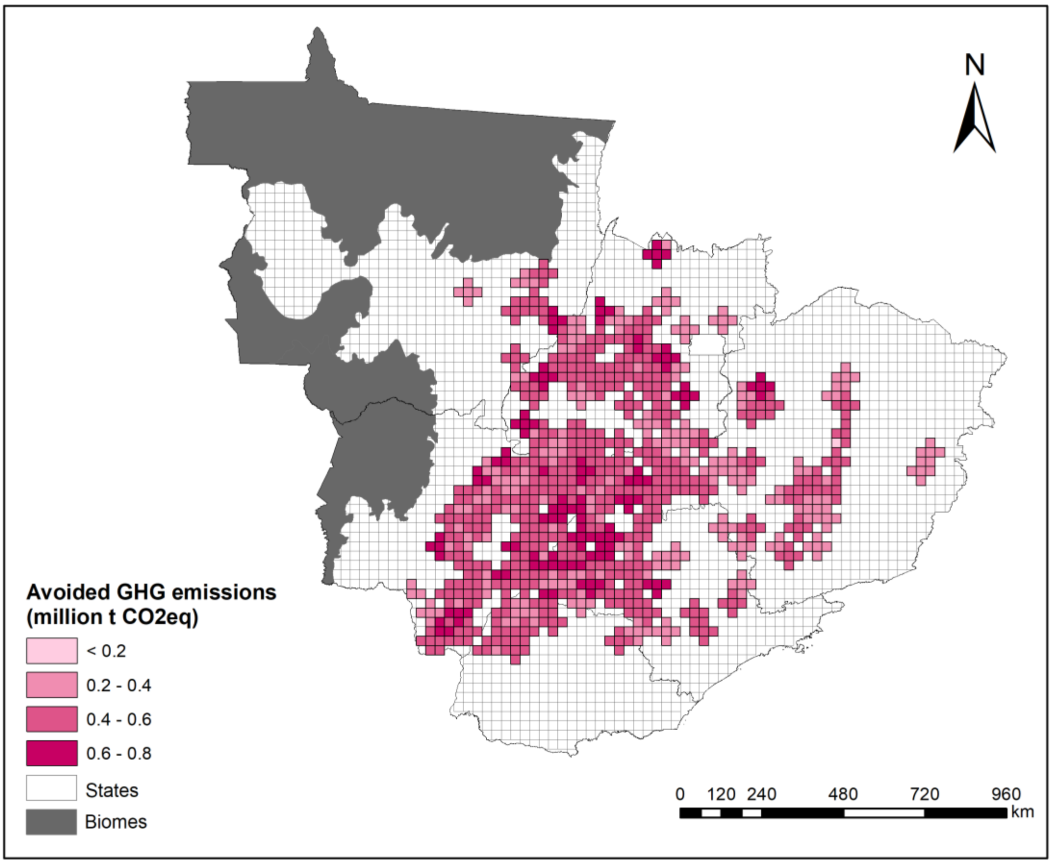

Figure 12: Spatially explicit potential of GHG avoided emissions in Tech1_Sugarcane

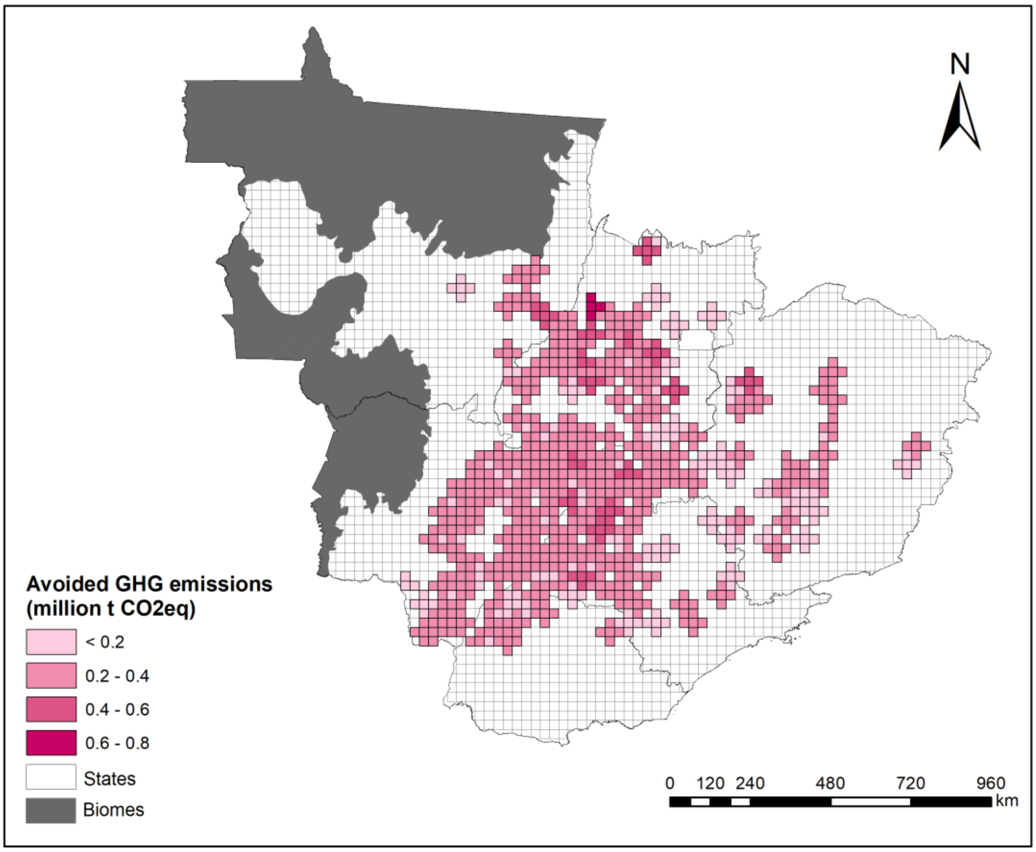

Figure 13: Spatially explicit potential of GHG avoided emissions in Tech2_Corn

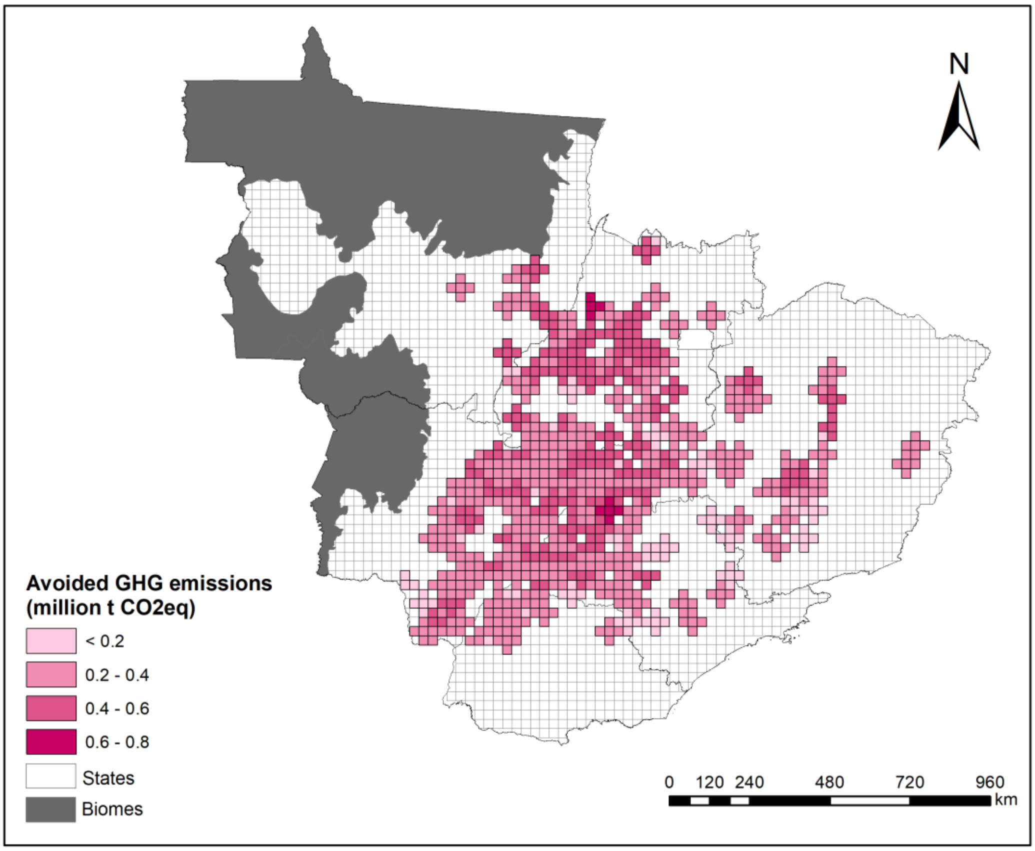

Figure 14: Spatially explicit potential of GHG avoided emissions in Tech3_Soybean

Finally, comparing the potential profits of all candidate sites, Tech3_Soybean present the highest values (Figure 17), mostly because of higher market value for biodiesel compared to soybean oil. In Tech1_Sugarcane (Figure 15), most of candidate sites would have profits of around 200 to 400 million R$ per year, equivalent to around 50 to 100 dollars. Due to lower biofuel production, Tech2_Corn (Figure 16) present the lower profits comparing to the other options.

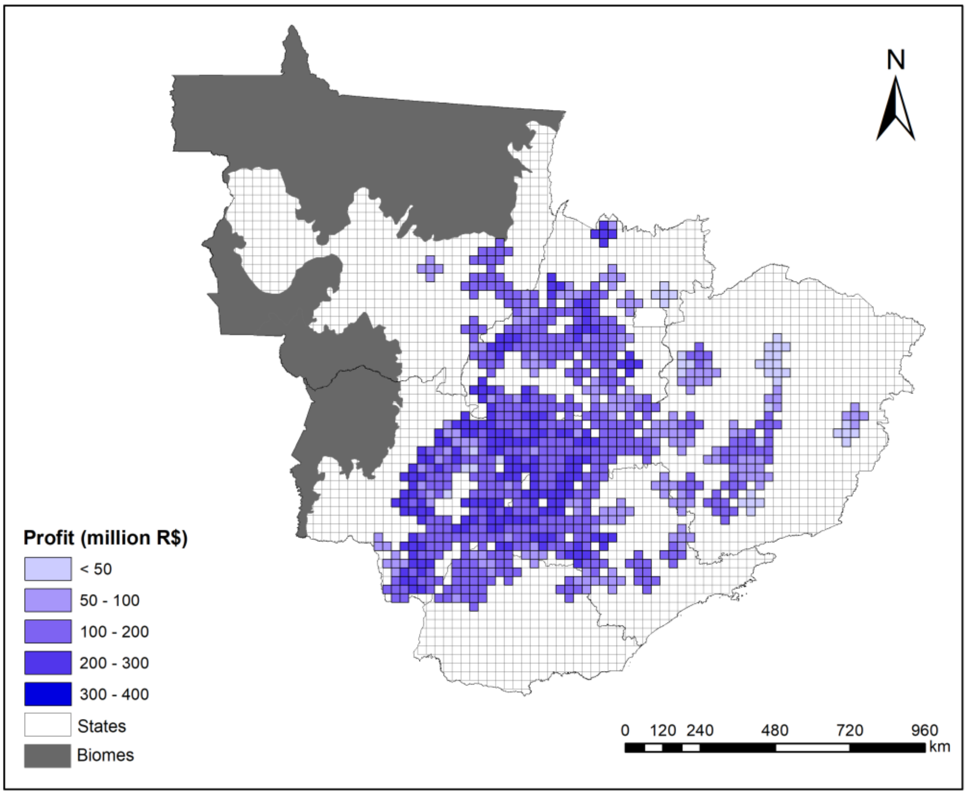

Figure 15: Spatially explicit potential of profits in Tech1_Sugarcane

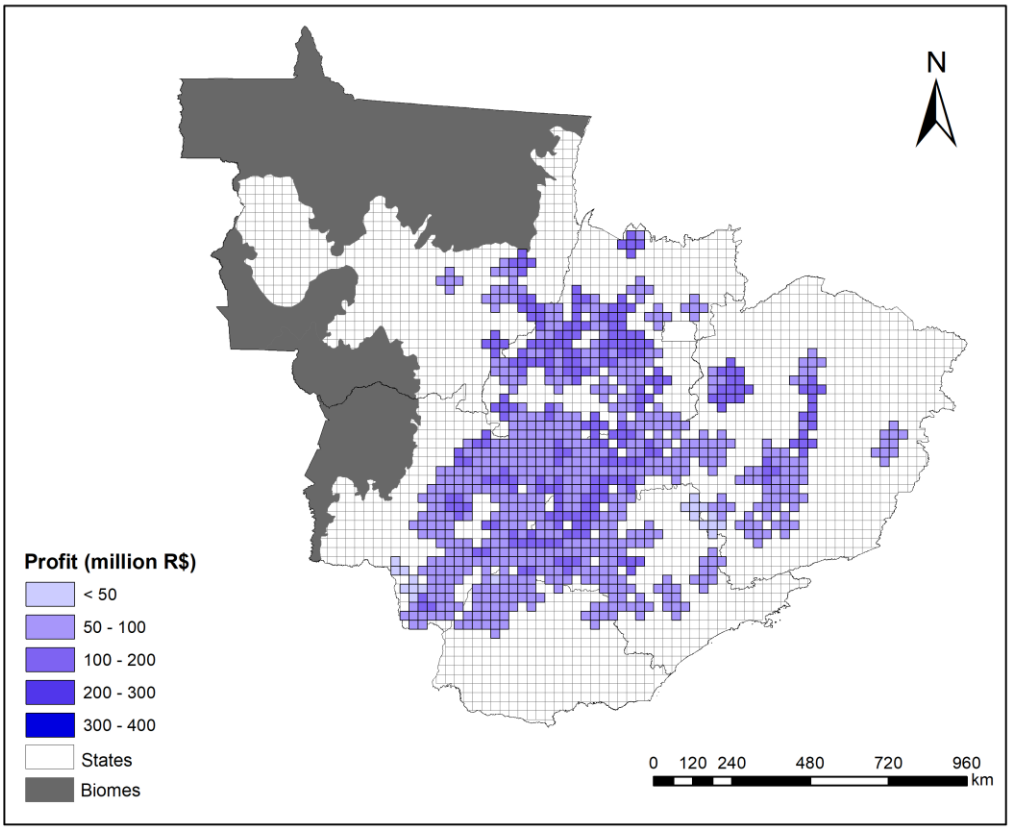

Figure 16: Spatially explicit potential of profits in Tech2_Corn

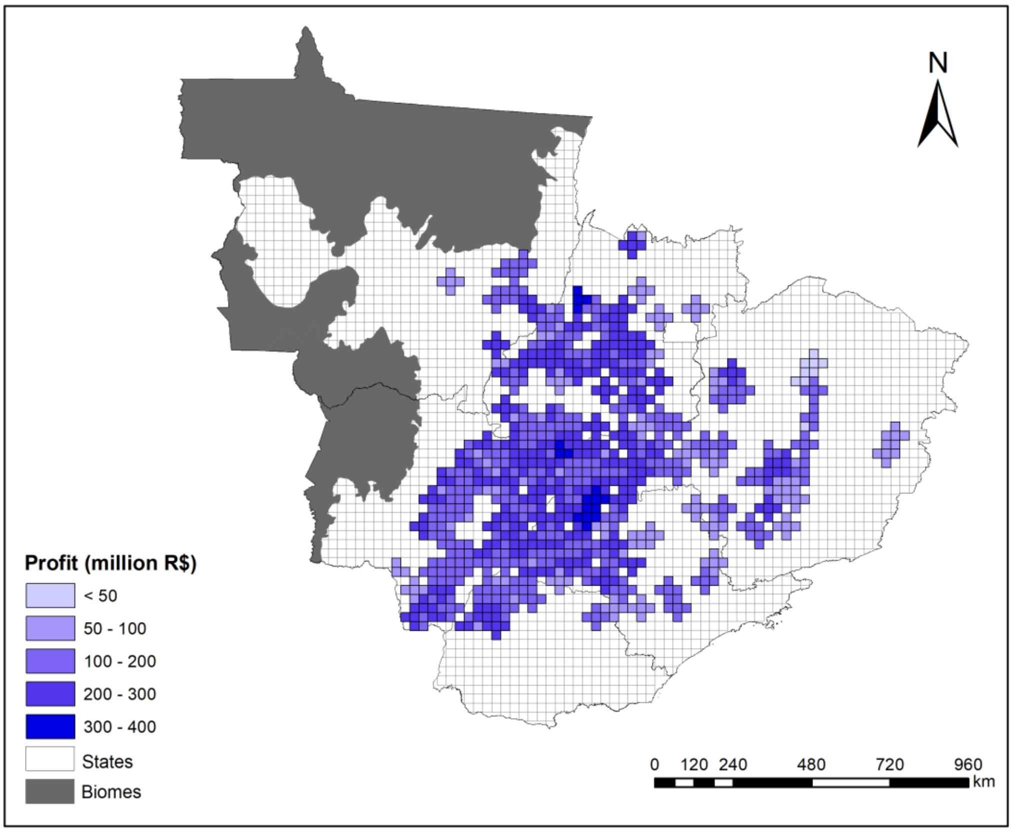

Figure 17: Spatially explicit potential of profits in Tech3_Soybean

In Figure 18 there is the sum of total potential of ethanol production, avoided GHG emissions and profits per technological option. The 89 billion liters produced in Tech1_Sugarcane (or 1.98 EJ per year) are 2 times more than the remaining volume demanded by SSP1 in 2030, after part of the demand is met by the current ethanol production of around 30 billion liters (CONAB, 2020). Even considering the expansion of Tech3_Soybean, that has the lowest potential among the options, 85% of SSP1 demand for 2030 could be met. For SSP3, that has the lowest ethanol demands, total ethanol produced in Tech1_Sugarcane would be 8 times higher than the remaining demand. Regarding potential to mitigate GHG emissions, Tech1_Sugarcane represents 15% of the total 900 million tonnes of CO_2eq that might be mitigated by 2030 according to Brazilian NDC, that established GHG emissions in 2030 must be reduced in 43% compared to the 2.1 GtCO_2eq emitted in 2005 (Brasil, 2015). Although, Tech1_Sugarcane resulted in best potentials to produce ethanol and to avoided GHG emissions, Tech3_Soybean was the best option considering profitability. It can be explained by revenues associated with biodiesel sell. When comparing Tech2_Corn and Tech3_Soybean, it is possible to observe biodiesel production increased potential avoided emissions, but when comparing to Tech1_Sugarcane to Tech3_Soybean, the production of biodiesel was not enough to surpass Tech1_Sugarcane potentials to avoided GHG emissions. It can be explained because the comparison of technological options was carried out considering the same area and sugarcane ethanol has the highest yields, thus more biofuel is produced. This tradeoff will be considered in the optimization that will be performed using BeWhere.

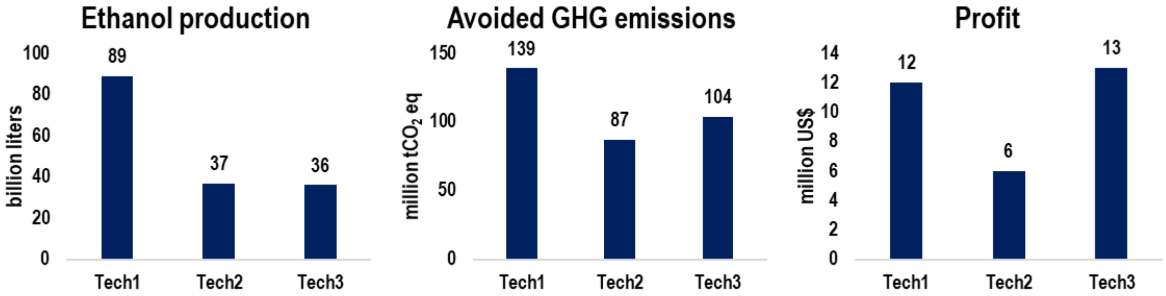

Figure 18: Comparison of potentials, avoided emissions and profitability in the three technological options

Uncertainties

The results presented in this study do not consider impacts of pasture conditions (e.g., level of degradability) on agriculture yields. Sugarcane modeled yields consider climatic characteristics of each region. We assumed a fixed cattle stocking rate of one cattle head per hectare in all study area, a spatially explicit livestock yield could influence the results, since all cattle heads should be fed with crops and by-products produced inside the integration boundaries, which means more animal feed production would be demanded in sites with higher stocking rates. Besides, corn and soybean plants animal feed are not a competitor with biofuel production, and in the case of sugarcane plants, it does not impact negatively on biofuel production (Souza et al., 2019; Sparovek et al., 2009). Future studies should include spatially explicit and modeled yield for corn, soybean and livestock stocking rate, and possible climate change impacts in crop yields.

The environmental sustainability impact was focused on calculation of GHG emissions. Regarding impacts on biodiversity, we excluded biodiversity hotspots for the available area for BLIS expansion, however no assessment was carried out to consider biodiversity losses and/or gains due to the replacement of pasture with crops (i.e., sugarcane, corn, soybean). Although carbon stocks associated land use change emissions can have significant contribution to overall life cycle emissions (Bordonal et al., 2016; Figueiredo et al., 2017), it was not carried out in this study. Also, no assessment of soil organic carbon emissions (SOC) and impacts of BLIS on water availability was performed in this study.

The integration as presented here happens with livestock at the final stage of production cycle (Souza et al., 2019, Picoli, 2017), where all cattle heads can be finished in feedlots. Detailed modelling should be carried out to understand the integration at all production cycle, such as cow and calf system. This initial stage of livestock production has limitations on the use of biofuels by-products as animal feed, and less land could be released.

Potentials of BLIS in Brazil

Despite the uncertainties of BLIS in this study, this production system has great potential to meet future ethanol demands and GHG mitigation targets. The integrated production can also contribute to zero deforestation, avoiding land use displacement (Souza et al., 2019). Also, it can provide reduction on land competition for food and energy production due to the use of bioenergy by-products as animal feed that replace or reduce grazing and crop production for feed purposes (Moreira et al., 2020; Popp et al., 2016). Studies have suggested that after pasture intensification, 37 to 50 million hectares could be available for bioenergy expansion without causing land use displacement (Alkimin et al., 2015; Lossau et al., 2015).

The results presented in this report show the full potential of the available area for expansion to meet future ethanol demands and GHG mitigation targets, as well as the spatially explicit avoided GHG emissions, supply chain costs, revenues and their variability according to locations. A spatially explicit sustainability assessment of BLIS is key to help to produce bioenergy without compromising feedstock availability, food security, land use, biodiversity, among others. Further optimization with BeWhere will allow to select the best candidate sites and the best technological option to meet the specific ethanol demands per SSP per decade.

Future bioenergy demands of projection studies rely largely on 2G ethanol (Andrade Jr et al., 2019; Jaiswal et al., 2017); however, worldwide cellulosic ethanol is still not produced in large volumes. To meet the future bioenergy demands with conventional biofuel production would require a large area, what could cause negative land displacement and impacts on natural vegetation and food production, often associated with large scale deployment of bioenergy (Cherubin et al., 2021; Frank et al., 2021; Humpenoder et al., 2018).

4. Final remarks

Bioenergy-livestock integrated systems are an important option for future land use management strategies in Brazil and have great potential to meet future bioenergy demand and GHG mitigation targets without land use displacement, biodiversity loss and competition with food production.

This study may support decision makers and encourage the formulation of enhanced public policies for the bioenergy sector based on the potentials to meet future energy demands and GHG mitigation targets, and to alleviate pressure on land use. Assessment of potential areas for implementation of BLIS was presented, indicating that their implementation would be possible in the Center-South region of Brazil. We believe that these results might help to support more assertive public policies regarding biofuel expansion in Brazil and contribute to achieve the ambitious targets assumed in the Paris Agreement.

There is still potential to explore and address uncertainties in the spatially explicit assessment of BLIS expansion in the country, such as refine crop and livestock yield, account for carbon stocks, impacts on water use, and consider complete cycle of livestock production.

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